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Clusters of contaminations have been identified within rehearsing choirs during the COVID-19 pandemic. In particular, singing and playing wind instruments are known to generate enhanced release of respiratory droplets, which are then transported by the expiratory flows. By tracking the air exhaled by professional opera singers and musicians from the MET Orchestra in New York City, we measure the spatial extent of the various air flows in opera. While loud singing is often associated with fast flows, professional opera singers and musicians are usually exhaling air flows slower than the air jets exhaled by a person breathing at rest. However, we identify a few situations leading to the release of rapid air jets that are able to enhance the transport of pathogenic droplets within an orchestra. Finally, we show how singing with a facemask and covering the bell of a wind instrument provide a strong reduction of the transport of respiratory droplets, in addition to the filtration features of a mask.

INTRODUCTION

Infectious respiratory diseases spread through the release of droplets carrying pathogens from an infected person [1–3]. Pathogenic droplets are known to be released during breathing, speaking, coughing, or sneezing [4–11]. Thus, during pandemics, large mass-gathering events have been the source of clusters of contaminations due to the presence of infected persons exhaling droplets in the presence of a large audience [12–15]. Among such events, live music was particularly affected by the COVID-19 pandemic as it was listed as a source of possible contaminations [16], which resulted in a global shift to online-performance for musicians. However, even in the absence of an audience, clusters of contaminations were identified within an orchestra during rehearsals [17, 18]. These events emphasize that activities like singing, or playing wind instruments, may be accompanied by an enhanced release of droplets [10, 19–21]. While the larger droplets sediment due to their own weight [1, 6], smaller aerosol droplets are carried by expiratory flows, and so are able to contaminate other musicians playing in the orchestra.

The number of droplets emitted by a human breathing, speaking, or singing has been quantified [5, 10, 19]. Previous studies have documented that the number of droplets released depends on loudness [7, 10, 19, 22] and pronunciation [9, 23] as plosives, or consonants sounds, lead to a substantial increase in the number of droplets emitted by a speaker [9]. Moreover, loud talking and plosive sounds generate faster flows, which are able to transport aerosol droplets over one meter within one or a few seconds [24]. It has been suggested that singing might generate faster flows than speaking [25, 26] carrying possible pathogenic droplets to larger distances [6]. Similar measurements have been made on people using various wind instruments, e.g., oboe, trombones or trumpets were identified as generating a larger number of droplets than other wind instruments [21, 27–29]. Nevertheless, a few recent studies report that the air flows emanating from instruments apparently decay to background levels at a close distance from the musician, ranging between 30 cm and 1.2 m [30–32].

While recent measurements focus on the musical air flows released from the bell of instruments, musicians and singers are generating a variety of air flows during a performance. For instance, the respiration of performers might enhance the transport of the droplets emitted during the performance as breathing and speaking is known to produce rapid air jets [24]. As air flows transport pathogenic droplets [6, 33–36], this question is crucial to determine the risk of infection, and to eventually issue new guidelines to ensure safer conditions during the performance of an orchestra [29]. In this paper, we systematically measure the distance reached by the various air flows emitted from a musician or a singer. By comparing our measurements during the performance with ordinary breathing or speaking, we identify situations where air flows from musicians might increase the risk of infection within an orchestra. In particular, we focus our measurements on professional opera singers and musicians. Indeed, one might expect that opera performances are at higher risk of infection due to the large number of wind instruments, and the spectacular loudness of opera singers. In this study, we track the air exhaled from individual performers by using two different visualization techniques, and we measure intrinsic properties of the air flows such as initial velocities and expiratory flow rates during performance.

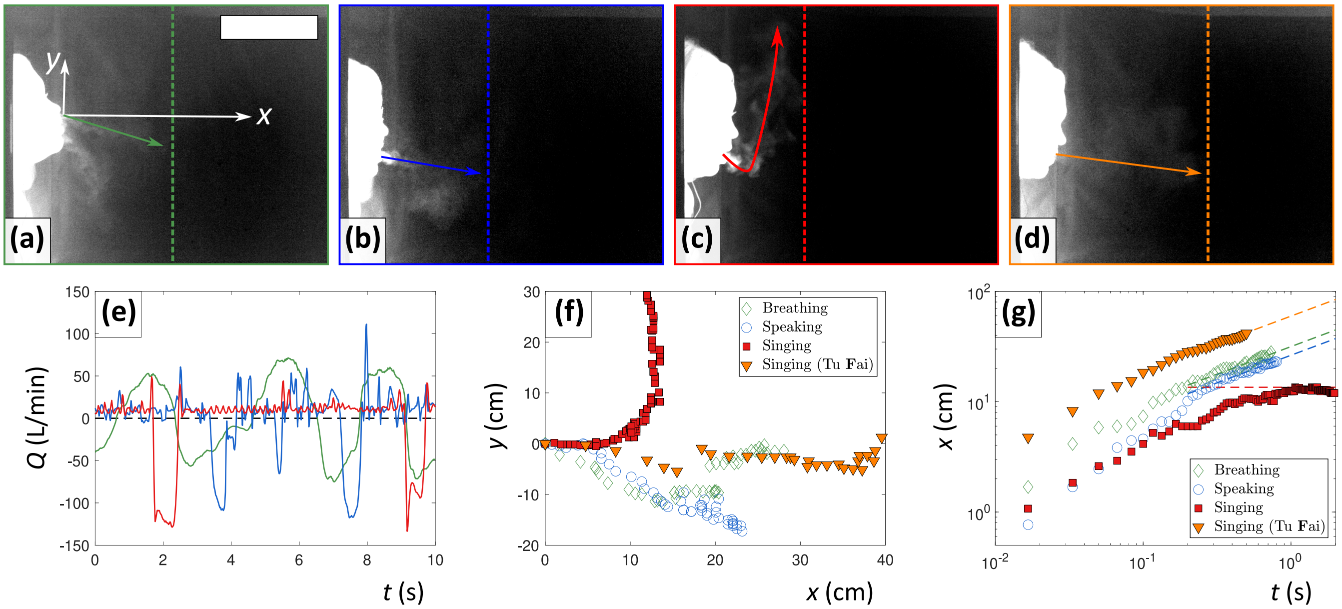

FIG. 1. Air flows exhaled by an opera singer. **a)** CO_2 jet breathed out from the nose of the singer during respiration in a performance. The scale bar represents 20 cm. **b)** CO_2 jet exhaled while the singer speaks the lyrics of the song. **c)** CO_2 jet exhaled while singing 'Casta Diva'; the warm exhaled air rises due to buoyancy. **d)** CO_2 jet exhaled while singing the 'F' from "Tu Fai." As the mouth is closing for the fricative 'F' sound, the air jet reaches a distance of several tens of centimeters within 200 ms. **e)** Expiratory flow rates $Q(t)$ measured during respiration at rest ($-60 < Q < 60$ L/min, in green), when the singer speaks the lyrics (blue data), and during the performance (red). **f)** Trajectories $y(x)$ of the front of the air jet exhaled by the singer during respiration (green diamonds), speaking (blue circles), singing with an open mouth (red squares), and singing the 'F' from "Tu Fai" (orange triangles). When flow speeds are lower (red data), the exhaled warm air rises due to buoyancy as seen in panel 1(c). **g)** Tracking of the horizontal front $x(t)$ of the air jet exhaled by the singer during respiration (green diamonds, initial velocity $V_0 \approx 1$ m/s), speaking (blue circles, $V_0 \approx 0.7$ m/s), and singing (red squares, $V_0 \approx 0.35$ m/s). When the mouth is closing (singing the 'F' from "Tu Fai"), the air travels faster (orange triangles, $V_0 \approx$ 2-3 m/s). All rapid jets continue their horizontal propagation at timescales larger than 1 s ($y \propto \sqrt{t}$ as seen on the blue, green, and orange dashed lines) whereas the singing with an open mouth saturates due to the rising buoyant flows (red dashed line).

EXPERIMENTS WITH MUSICIANS

In the course of our experiments, we measured air flows on three professional female opera singers (two sopranos and one mezzo-soprano) and a variety of wind instruments (clarinet, flute, french horn, oboe, piccolo, trombone, trumpet). All performers were world-renowned musicians and singers affiliated with the MET Orchestra in New York City. A list of the performers and the musical pieces studied is provided in Supplementary Table S1 [37]. We combined two flow visualization techniques to track the exhaled air during the performance. First, we tracked the warm exhaled CO_2 using a high-speed infrared camera (FLIR X6900SC). The high-performance cooled sensor operates in the mid-wave range of the infrared spectrum (1.5 - 5 μm) and a filter in the absorption range of CO_2 (4.2 μm) enables the tracking of the exhaled CO_2 [38–40]. Both the opera singers and the musicians performed beside a dark, non-reflective curtain, which provided a uniform background at the ambient temperature. To avoid major disturbances from the background flow in the experimental space, additional curtains were used around and above the human subjects. As shown in Fig. 1(a-d) and Movie S1 for the case of a soprano, the warm face and warm exhaled CO_2 are visible in contrast with the dark background. Hence, the exhaled CO_2 can be tracked as it flows away from the singer. However, both thermal homogenization and mixing with the surrounding air lead to a decreased concentration of the warm exhaled CO_2 over time. At large distances and/or timescales, the tracking of the exhaled CO_2 is made impossible by the limited sensitivity of the infrared camera.

To validate the detection of the exhaled air by the warm CO_2, we also track directly the exhaled air with an artificial fog illuminated by a laser sheet [24], and imaged with a high-speed camera (Phantom v7). The artificial fog was dispensed using a fog machine (American DJ; fog solution by Froggys Fog) within an experimental chamber made by curtains and transparent plexiglass walls to limit the background flow inside the experimental space. Fog droplets were made visible by a green ($\lambda = 532$ nm) laser sheet oriented vertically from the top of the experimental room. The position of the laser sheet was centered on the bell of the instrument or on the face of the performer (wearing laser safety glasses) to detect air flows emanating from the mouth and the nose of the human subject. The bright fog droplets contrast with the dark air exhaled by the performer, as seen in Movie S2 for the case of a soprano.

Finally, we recorded the expiratory flow rates of singers and musicians during individual performances. Singers were asked to breath, speak, and sing into a cardiopulmonary resuscitation (CPR) mask (MCR Medical), covering both nose and mouth, and connected with medical corrugated air tubing to a flow meter [41]. Similar approaches were used with musicians who were asked to breath and to play while the mouth piece of the instrument was adjusted inside the CPR mask.

RESULTS

Opera singers

Our data allows us to describe quantitatively the exhaled flows from singers and musicians. We compare the expiratory flow rates, the flow velocities, and the spatial extent of the air flows between situations ranging from breathing at rest to musical performance. In Fig. 1, we report the flows exhaled by a professional opera singer (a soprano singing 'Casta Diva'). Similar figures are provided in the Supplementary Figures S1-3 based on multiple measurements of air flows including two other opera singers. Infrared imaging of the warm CO_2 exhaled by a singer are shown in Fig. 1(a-d). The trajectory of the air flows are highlighted with a colored arrow, and the horizontal extent of the air flows is shown by the colored vertical dashed lines. During the performance, the singer alternates between breathing [Fig 1(a), green frame] and singing [Fig 1(c-d), red and orange frames].

Two situations were identified during the singing. The general case (in red) contrasts with the rapid jet flows emanating from sounds requiring a closed mouth. In Fig. 1(d), we report the particular example of the 'F' pronounced by the singer at the end of the 'Casta Diva' song while singing "Tu Fai." This fricative consonant sound requires closing the mouth [42, 43], in contrast with the rest of the song where the singer maintains a wide open mouth to sing vowel-based sounds characteristic of Italian opera, as seen in Fig. 1(c) and Supplementary Movie S1. Measurements were also made while the singer was speaking the lyrics of the song [Fig. 1(b), blue frame].

The expiratory flow rates $Q(t)$ recorded during breathing, speaking, and singing are presented in Fig. 1(e). The breathing pattern (in green) measured for a singer at rest is composed of alternate phases of inhalation ($Q < 0$) and exhalation ($Q > 0$) with peaks reaching values around 60 L/min. Speaking (blue data) and singing (in red) exhibit a different pattern for $Q(t)$. Indeed, inhalations tend to be shorter and more intense (down to -130 L/min) and exhalations are affected by the pronunciation of words. While speaking leads to a succession of irregular peaks of positive expiratory flow rates up to 50 L/min, exhaled flow rates during singing (red) exhibit remarkable stability around a roughly constant value at a lower flow rate $Q \approx 10$ L/min. Our measurements thus demonstrate the exquisite control of the exhaled flow rates by a professional opera singer. This control is only affected by the presence of a slight oscillation due to the use of a vibralto technique [44].

Using movies recorded with the infrared camera (see Supplementary Movie S1), we track the air fronts exhaled during breathing, speaking, and singing; x and y denote, respectively, the horizontal and vertical directions. The trajectories $y(x)$ associated with the four situations described in Fig. 1(a-d) are shown in Fig. 1(f). In most of the cases the flows have a straight trajectory (blue, green, and orange data), also shown by the straight arrows in Fig. 1(a-b,d). The results indicate that exhaled air forms air jets emanating from the mouth or the nose of a person [6, 24, 40]. Conversely, singing with an open mouth leads to a curved trajectory (red squares) as the warm exhaled CO_2 rises at a distance of about 10 centimeters from the singer. This buoyant flow, due to the warm exhaled air, can be seen in Fig. 1(f). While the buoyancy-driven redirection of the warm air ultimately affects all expiratory flows [6], slower air flows induce a more significant rise of the exhaled air, a phenomenon also observed in the case of the reduced speed of the exhaled air caused by a face mask [40, 45]. As a consequence, the horizontal propagation $x(t)$ of the front of the exhaled air saturates after about one second at a distance of 15 centimeters from the singer, as shown by the red dashed line in Fig. 1(g). Conversely, speaking and breathing induce larger horizontal extents x of the exhaled air, reaching distances of about one meter within a few seconds [24] and growing like a turbulent air jet, $x \propto \sqrt{t}$ (blue and green dashed lines). This observation was consistently repeated on various instances of air flows measured during the performance as seen in Supplementary Figure S1. Despite the apparent complexity and diversity of air flows associated with singing, our results further demonstrate that a professional opera singer generates slower and more localized air flows than normal breathing. However, the tracking of the exhaled air during the singing of a consonant sound (orange triangles) demonstrates the existence of rapid turbulent jets during the song.

These results can be understood by the measurement of the flow rates displayed in Fig. 1(e). As the flow rates during performance (red data) are roughly constant at a value six times smaller than breathing, the flow velocities of the exhaled air are expected to be significantly slower while singing with an open mouth. However, when the opera singer is closing her mouth to pronounce a consonant sound, the constant flow rate during singing re-

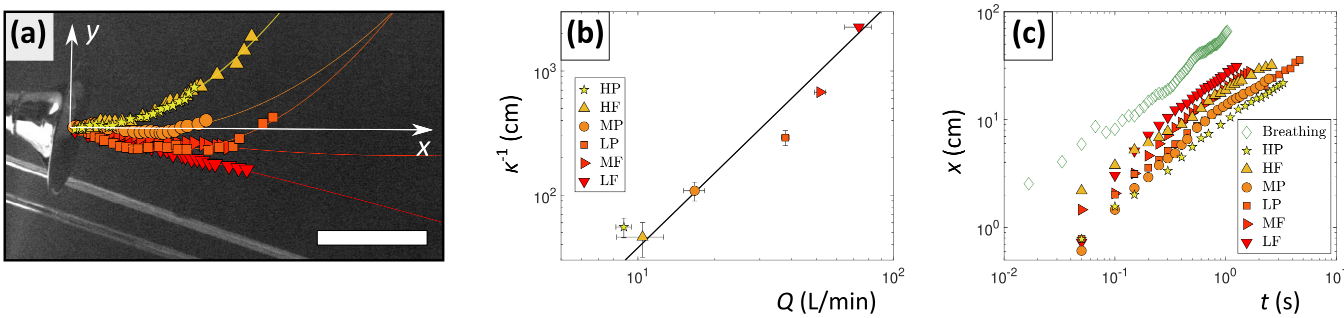

FIG. 2. Air flows emanating from a trombone. **a)** Trajectories $y(x)$ of CO_2 jets emanating from the bell of a trombone during a performance. The individual trajectories represent different sustained notes of various flow rates ranging from 9 L/min ('High Piano', yellow stars) to 80 L/min ('Low Fortissimo', red triangles). All trajectories can be fitted by a parabolic shape (solid lines). The scale bar represents 20 cm. **b)** Radius of curvature κ^{-1} of the jet trajectory as a function of the exhaled flow rate Q during different sustained notes. κ^{-1} is measured by fitting the trajectories by a quadratic equation as shown in panel 2(a). The flow rate Q is measured as the musician plays through the mouthpiece of the instrument connected to a flow meter by a medical tubing (see Supplementary Figure S4). Data are averaged on a minimum of 3 measurements. Error bars represent the standard deviations. The solid line represents $\kappa^{-1} \propto Q^2$. **c)** Horizontal front $x(t)$ of the jets emanating from the bell ($x = 0$, $t = 0$). All sustained notes lead to air jets of initial speeds 0.1 m/s $\leq V_0 \leq$ 0.45 m/s, which is slower than standard breathing exhaled from a human at rest (green diamonds, $V_0 \approx 1$ m/s).

ported in Fig. 1(e) induces a significant increase in flow velocities and leads to the formation of rapid turbulent jets. These findings can be extended to other singers (see Supplementary Figures S2-3 and Movies S3-4). Moreover, consonant sounds, such as the 'F' in Fig. 1(d), lead to an increase of droplets released similar to recent reports on speaking [9, 23].

Our results indicate that professional opera singers have great control over the exhaled flow rates during their performances as they train to maintain loud constant tonalities up to 10-20 s without inhalation. Maintaining a low value of flow rates is thus a typical achievement of opera singers, as highlighted by the legendary singing practice using a lit candle near the mouth [46]. Our findings for opera singers might not be valid for other kind of music, such as rap with a more intensive use of plosives and consonant sounds [23].

Wind instruments: Brass instruments and clarinet

We also performed measurements of the air flows emanating from a variety of wind instruments played by professional musicians. Among all tested instruments, trombones are known to require larger expiratory flow rates [47] and to generate an enhanced number of droplets [28, 29]. Using the infrared camera, we track the warm CO_2 within 50 centimeters from the bell of the instrument. In Fig. 2, we report the tracking of the exhaled air from the bell of a trombone while the musician is playing long low (denoted 'L'), medium ('M') and high ('H') notes with a crescendo intensity from soft (piano, 'P') to loud tones (fortissimo, 'F'). The trajectories $y(x)$ of the various notes are represented in Fig. 2(a), with solid symbols from 'High Piano' ('HP', yellow stars) to 'Low Fortissimo' ('LF', red downward triangles). For most of the notes, the warm CO_2 does not follow a straight trajectory and rises due to buoyancy (see Supplementary Movie S5).

All trajectories can be fitted by the equation $y = \kappa x^2 + \tan(\alpha)x + y_0$ (solid lines), with κ the curvature of the jet, y_0 the adjusted origin of the jet ($y_0 \approx 0$) and α the angle between the horizontal line (x axis) and the initial orientation of the jet. While the orientation of the jet varies slightly depending on the exact position of the instrument during the performance, the curvature of the jet seems to depend strongly on the note played.

The flow rate Q was measured using a flow meter (see Supplementary Figure S4). In Fig. 2(b), the radius of curvature of the jet κ^{-1} is represented as a function of the expiratory flow rate Q associated with the note played. The data in Fig. 2(b) are averaged over a minimum of three notes, and error bars represent the standard deviations of our measurements. The radius of curvature κ^{-1} of the air flows increases quadratically with the flow rate, as shown by the fit (solid line) of equation $\kappa^{-1} \propto Q^2$. This result is in good agreement with a balance between inertia and buoyancy leading to the equation $\kappa^{-1} \propto \frac{\rho Q^2}{\Delta\rho g}$ with ρ the density of air and $\Delta\rho$ the difference of density between the ambient air and the warm exhaled air [40]. The agreement between experimental data on the trombone and the model indicate that the air emanating from the bell of the instrument is rising due to buoyancy. This rise limits the horizontal extent of the air jets from the instrument similar to our reports from opera singers in Fig. 1. In addition, the measurement of the radius of curvature gives the distance at which the air is rising and appears to depend on the note, as louder ('Fortissimo')

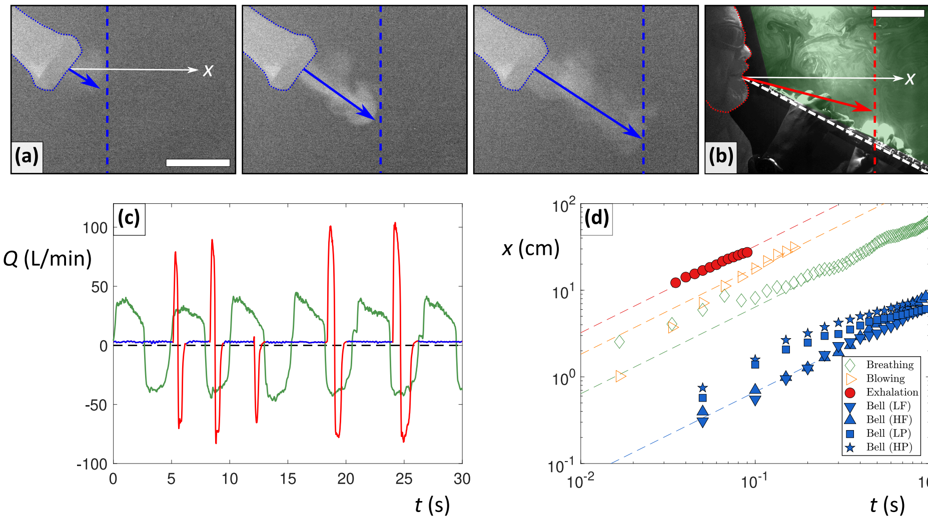

FIG. 3. Air flows around an oboe. **a)** Sequence of images (timestep of 333 ms) of a CO_2 jet emanating from the bell of the instrument during the performance. The position of the front of the jet is tracked (blue arrows). The horizontal position $x(t)$ of the jet front is highlighted with the vertical blue dashed lines. The scale bar represents 3 cm. **b)** Tracking of the exhaled air from the musician's mouth during a swift exhalation (see Movie S11). The air front is tracked (red arrow) within an artificial fog illuminated by a laser sheet (green area). The scale bar represents 10 cm. **c)** Expiratory flow rates $Q(t)$ measured during a respiration at rest ($-40 < Q < 40$ L/min, in green) and during the performance while the musician successively releases a constant small flow rate of air during the notes ($Q \approx 3$ L/min, in blue) and breathes out air during respirations (in red) made of swift exhalations (up to 100 L/min) followed by rapid inhalations ($Q < 0$). **d)** Tracking of the horizontal front $x(t)$ of the air jet from the bell during the performance (blue data, initial velocity 0.07 m/s $\leq V_0 \leq$ 0.3 m/s), from the mouth during a standard respiration (green diamonds, $V_0 \approx 1$ m/s), while blowing (orange squares, $V_0 \approx 2$ m/s), or during a swift expiration during the performance (red squares, $V_0 \approx 3$ m/s). Solid symbols are measured during a musical performance and open symbols on a human subject at rest. Dashed lines are guides for the eyes based on linear fits of the data. 'LF', 'HF', 'LP', and 'HP', respectively, mean 'Low Fortissimo', 'High Fortissimo', 'Low Piano', and 'High Piano'.

and lower notes generate faster flows. For instance, the radius of curvature varies from a few tens of centimeters for 'High Piano' up to a few meters for 'Medium Fortissimo'. More dramatically, the tracked CO_2 during a 'Low Fortissimo' note does not appear to rise due to buoyancy, as shown by the red triangles in Fig. 2(a), leading to an estimated radius of curvature larger than 10 m.

To characterize the dynamics of the exhaled air, we report in Fig. 2(c) the horizontal propagation $x(t)$ of the air front exhaled from the bell of the instrument during the performance (solid symbols). All notes induce a horizontal spatial extent of the air front smaller than 50 cm within 1-2 seconds. More importantly, data recorded during the performance (solid symbols) show that the air flows emanating from the bell of a trombone are significantly slower than the data recorded for a person breathing at rest (green open symbols) [40]. Thus, faster air flows during a performance arise from the respiration of the musician rather than from the musical instrument. This result is consistently observed over the entire range of the musical spectra from low to high notes with soft (piano) to loud (fortissimo) intensities and with a multitude of other wind instruments such as clarinet, french horn, and trumpet (see Supplementary Figures S5-7, and Movies S6-8).

Other air flows were tracked on the wind instruments, such as slow air flows from the keys of a clarinet (Supplementary Figure S5). All measurements of air flows emanating from the bell or keys of the instruments were shown to be consistently slower than air flows associated with the respiration of the musician. Moreover, our measurements on professional musicians fail to capture any leakage at the mouthpiece, which we attribute to the skills of the professional musicians taking part in the study and are expected to be different from amateur musicians.

Wind instruments: Flute and Oboe

Results for a few wind instruments exhibit different features at the mouth of the musician. For instance, flute and piccolo require the release of rapid air jets tangent to the instrument's lip plate. As evident in Supplementary Figure S8 and Movie S9 for the flute and Movie S10 for the piccolo, the rapid air flows from the mouth of a musician playing flute (or piccolo) appear to be similar to the air flows measured during breathing and speaking. Playing a flute thus creates conditions for rapid transport of droplets over distances around a meter within 1-2 seconds. More dramatically, other rapid air flows can be identified when playing the oboe, as described next.

Air flows were tracked from the bell of an oboe [Fig. 3(a)] using infrared imaging of warm exhaled CO_2 and from the mouth of the musician [Fig. 3(b)] using a fog illuminated by a laser sheet. Oboists are known to perform at low exhaled flow rates requiring breath-holding ability [47]. Expiratory flow rates $Q(t)$ from a musician are reported in Fig. 3(c). Green data represent respiration of the musician at rest reaching values up to 50 L/min. During the performance, the musician exhales according to a regular pattern. The exhaled flow rate is roughly constant while a tone is played ($Q \approx 3$ L/min, blue data), but rapid and brief exhalations are noticeable between notes, prior to the next inhalation (red data). The swift exhalations from the oboist reach values around 100 L/min. The low flow rates associated with the music (blue data) induce slow air flows emanating from the bell of the instrument. The air front reaches over 10 centimeters within 1 second as seen in the sequence of infrared images in Fig. 3(a).

The horizontal extent $x(t)$ of the air flows is reported in Fig. 3(d). As discussed earlier for other wind instruments, the air flows associated with the music (blue data) of initial speeds 0.07 m/s $\leq V_0 \leq$ 0.3 m/s are slower and more localized than air flows during breathing (green open diamonds, $V_0 \approx 1$ m/s). However, the swift exhalations from the oboist, tracked from the mouth of the musician using fog imaging [see Fig. 3(b) and Movie S11], are faster than respiration at rest (red circles). Their initial speed ($V_0 \approx 3$ m/s) and spatial extent appears to be even larger than typical measurements from individuals blowing exhaled air (orange open squares, $V_0 \approx 2$ m/s) [40]. In addition to the excess of droplets emitted by an oboist during a performance [28], the necessary breathing of the musician causes much faster flows than the ones considered in the literature [29].

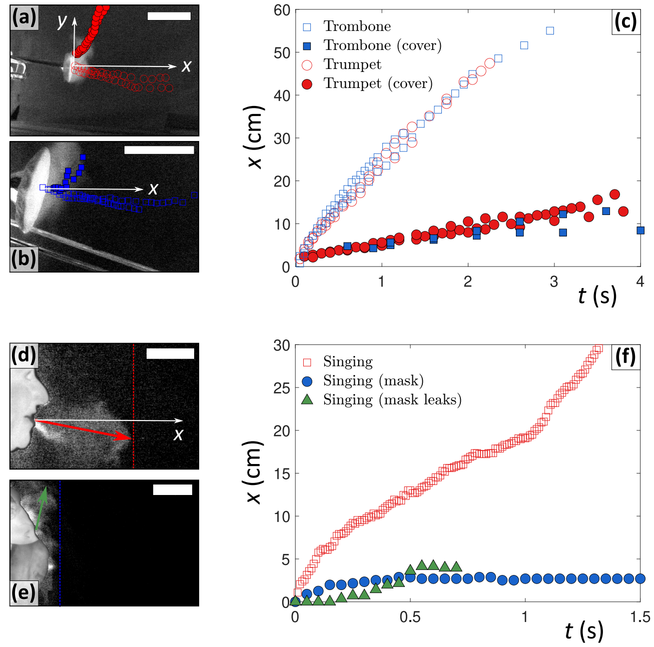

FIG. 4. Mitigation of musical air flows. **a)** Trajectories $y(x)$ of CO_2 jets emanating from the bell of a trumpet while playing a 'Low Fortissimo'. The exhaled air is rising and limited in terms of horizontal propagation when the bell is covered with a tissue (filled symbols) compared to the trajectories from an uncovered bell (open symbols). The scale bar represents 20 cm. **b)** Trajectories $y(x)$ of CO_2 jets emanating from the bell of a trombone while playing a 'Low Fortissimo'. The exhaled air is rising and limited in terms of horizontal propagation when the bell is covered with a tissue (filled squares). The scale bar represents 20 cm. **c)** Horizontal position $x(t)$ of the front of the CO_2 jet emanating from the bell of a wind instrument. Both trombone (blue squares) and trumpet (red circles) show the same behavior: the spatial extent of the jet is limited by the use of a cover (filled symbols). **d)** CO_2 exhaled by a soprano singing 'Brunhilde's Immolation'. The jet (red arrow) reaches several tens of centimeters. The scale bar represents 10 cm. **e)** CO_2 around an opera singer wearing a face mask during a performance. The CO_2 only propagates horizontally over few centimeters (blue dashed line). Leaks of CO_2 from the edge of the mask induce a rising flow (green arrow). The scale bar represents 10 cm. **f)** Horizontal position $x(t)$ of the front of the CO_2 jet during a performance. The face mask restricts the horizontal propagation of the jet to a few centimeters (blue filled circles). The saturation seen for the blue data (circles) corresponds to the rise of the buoyant jet.

Face masks and bell covers

While only few situations during a performance lead to the release of rapid air jets able to transport droplets over 1 m within few seconds, the mitigation of all expiratory air flows is necessary to limit a risk of contamination arising from the continuous release of droplets during the performance. Among other considerations including ventilation techniques [29], facemasks are widely used to filter pathogenic droplets emitted and/or inhaled by a person [48–53]. Masks also reduce the typical speed of expiratory flows transporting possible contaminated droplets [40, 45]. Similarly, droplets emitted by singers can be filtered by a mask, and covered bells for instruments have been studied as a public health strategy within an orchestra [21, 30, 32, 54].

The influence of a cover on air flows from the bell of a trumpet or a trombone is shown in Fig. 4(a-c) and Movies S12-13. Trajectories of the air jets from the bell of a trumpet are affected by the presence of a cover, which induces an enhanced redirection of the flow by buoyancy, as seen in Fig. 4(a). The same behavior occurs for the flow from the bell of a trombone [Fig. 4(b)]. The horizontal extent $x(t)$ of the air flow reported in Fig. 4(c) is thus reduced significantly as air from a cover bell rises within 10 cm of the bell of both instruments (solid symbols), whereas it reaches distances around 60 cm in the uncovered case.

Face masks have the same influence on the air flows exhaled by an opera singer as seen in Movie S14. A soprano emits air flows reaching distances around 30 cm within one second, as shown in Fig. 4(d). When wearing a mask, the warm exhaled CO_2 is only noticed within a few centimeters of the mask, as indicated by the blue vertical dashed line in Fig. 4(e). The presence of the leaks (green arrow) around the mask shows that some unfiltered air can escape from the mask. However, the leakages induce air jets of reduced velocity and low horizontal extent, as seen in Fig. 4(f).

CONCLUSION

While singing and playing wind instruments produce an enhanced number of droplets, the usual air flows in the opera, from singers and musicians, tend to be slower during a performance than normal breathing or speaking. Our results suggest that the transport of pathogenic aerosol droplets is mostly driven by the breathing, rather than exhalations tied to play, of performers during the performance. However, we have identified a few situations where air flows, generated by professional musicians in the opera, are faster: the pronunciation of consonant sounds by singers, the rapid air jets used by a flutist to perform, and the swift exhalations from an oboist. The existence of rapid air flows may be relevant to adjust safety guidelines for an orchestra such as rearranging the position of musicians within an orchestra [29]. Indeed, by considering the diversity of air flows during a performance, mitigation strategies within an orchestra have to focus on the fastest flows leading to the most extensive transport of droplets. In addition, to mitigate the local transport of droplets from the largest emitters of droplets such as the brass instruments [28, 29], our results suggest to focus the attention on instruments like the flute and the oboe. Finally, the use of masks by singers, or covering the bell of instruments, reduces significantly the transport of aerosol droplets in addition to their efficient filtration [21, 32] similarly to common observations with humans breathing or speaking [40, 45, 55]. While the acoustic performance of a mask or cover might remain a possible concern [32, 56, 57] for opera devotees, they obviously provide safer conditions to orchestras and choirs during performances and rehearsals in the time of a pandemic.

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